Original Paper

An Estimation Method for Solar Radiation Intensity Using a Web Camera

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This paper proposes an estimation method for solar radiation intensity, using pictures taken by a web camera. This approach makes use of the relationship between solar radiation intensity and the color properties of pictures. A clear day model and a cloudy day model are introduced as fourth-order polynomial expressions consisting of the brightness value and saturation as color properties. Furthermore, a hybrid model that can be switched to either the clear day model or the cloudy day model, according to the weather as determined by Japan Meteorological Agency, is developed. The validity of the proposed method is examined using the mean absolute error. Based on the study results, the proposed method can effectively measure solar radiation intensity.

本論文は、webカメラで撮影した画像を使用して日射強度を推定する手法を提案する。この手法は、画像の色情報と日射強度の相関を利用する。快晴日モデルと曇天日モデルを色情報である明度と彩度の4次元多項式で表現し、開発したハイブリッドモデルは気象庁が測定した天気に従って快晴日モデルと曇天日モデルを切り替える手法である。提案手法の有効性は平均絶対誤差により評価される。実験の結果、提案手法は日射強度を効果的に計測できる。

Key Words

Photovoltaic generation, Solar radiation intensity, Web camera

1. Introduction

In recent years, resource depletion and global warming have been recognized as serious issues. Public and technical attention is increasingly focused on the use of photovoltaic (PV) generation to address these issues. However, the output power of PV systems fluctuates strongly with changes in temperature and solar radiation intensity, due to weather and geographic conditions. PV systems may therefore have detrimental impacts on power grids when a large number of PV systems are installed¹⁾. Therefore, it is essential to reduce the output power fluctuations associated with PV systems. The most important information for realizing this objective is solar radiation intensity.

Observation sites that measure solar radiation intensity are limited in number, and there are 48 meteorological observatories that have been established by Japan Meteorological Agency (JMA). It is infeasible

to install pyranometers at all PV sites, therefore, various methods for estimating solar radiation intensity over a wide area have been proposed. A simple estimation method for solar radiation intensity using ground pictures taken by a camera was previously reported by Takigawa²⁾. However, this method does not sufficiently explain the relationship between solar radiation intensity and the color properties of pictures that are dependent on weather conditions.

This paper proposes a simple estimation method for solar radiation intensity using a web camera, and utilizing a clear day model and a cloudy day model. First, the relationship between the observed solar radiation intensity and the color properties of pictures taken by the web camera is investigated. Next, approximate expressions are modeled, using a regression analysis based on the observed solar radiation intensity and color properties. A clear day model and a cloudy day model are then developed for fundamental estimation models. Furthermore, a hybrid model is switched to either the clear day model or the

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cloudy day model, according to the time zone and weather conditions. Finally, the solar radiation intensity is estimated by the proposed estimation method using the web camera pictures. The validity of the estimation method is then evaluated using the mean absolute error (MAE).

2. Experimental Conditions

2.1 Study location

The web camera is installed on the 4th floor of Engineering Building No. 3, at Okayama University. Pictures taken from the north of this building are stored in a computer every 10 s. The time period during which pictures are taken is from 5:00 to 19:00 (Japan Standard Time (JST)) every day. The captured picture is filtered by a median filter to remove noise. An example of a picture taken by the web camera is shown in Fig. 1. The slate roof indicated by the circle in this figure is the analyzed area.

Fig. 2 shows the experimental setup. The pyranometer is installed on the roof of Engineering Building No. 3 at Okayama University, instead of in the analysis area. The instrument faces south at an inclination of 20° . Solar radiation intensity data are obtained every 2 s using the pyranometer. There is little difference in solar radiation

intensity between the observation point and the analysis area.

2.2 Correlation between solar radiation intensity and the color properties of pictures

Correlations between the observed solar radiation intensity and color properties (HSV values) on a clear day and a cloudy day are shown in Fig. 3. H, S, and V describe the color properties in terms of hue, saturation, and the brightness value, respectively. Each point in these figures represents an average value obtained during 1 min of time. The solar radiation intensity and brightness values show a positive correlation, while the solar radiation intensity and saturation display a weakly negative correlation. On the other hand, there is no correlation between the solar radiation intensity and hue. These features are similar throughout the time period of study, despite differing weather conditions.

Fig. 4 shows correlations between the solar radiation intensity and brightness values in the morning and in the afternoon on a clear day. The morning (AM) and afternoon (PM) values are compared at 12:00 (JST). The correlation between solar radiation intensity and morning values differ by a small amount as compared to the afternoon. This

Fig. 1 A picture taken by the web camera

Fig. 2 Experimental setup

(a) On a clear day (Nov. 1, 2013)

(b) On a cloudy day (Oct. 18, 2013)

Fig. 3 Correlation diagrams

Fig. 4 Correlations in the morning and the afternoon on a clear day (Nov. 1, 2013)

difference is caused by light reflected from the surrounding buildings, and atmospheric conditions.

2.3 Weather information and target period

The weather types are defined by JMA based on the definition as shown in Table 1³⁾. Weather types, with the exception of rain, are expressed using the cloud cover. This weather data is based on meteorological observation. The data are collected at the central point of Okayama city, 34°

Table 1 Definition of weather type

Weather	Cloud cover and conditions
Clear	Cloud cover: 0 to 1
Partly sunny	Cloud cover: 2 to 8
Slightly cloudy	Cloud cover: 9 or more High altitude cloud layers are more prevalent than the amount of mid- and low altitude clouds. Rain is absent.
Cloudy	Cloud cover: 9 or more Mid- and low altitude clouds are more prevalent than the amount of high altitude clouds. Rain is absent.
Rainy	Rain is present.

Fig. 5 Appearance hours of each type of weather from 6:00 to 18:00 during the observation period

39.6° N, 133° 55.0° E at 2.8 m elevation, and presented by JMA Okayama Local Meteorological Office.

The observation and estimation time period is from Oct. 16, 2013 to Dec. 1, 2013, with the exception of several unobserved days. There are 5 types of weather present during this period. The appearance hours for each type of weather from 6:00 to 18:00 (JST) is calculated during the observation period⁴⁾⁵⁾ and is shown in Fig. 5.

3. Approximate Expression of Solar Radiation Intensity by Color Properties

3.1 Approximate expressions

The approximate expressions of solar radiation intensity are represented by polynomial equations, based on the correlation between solar radiation intensity and color properties. The approximate expression is given by:

$$E = a_4 \cdot V^4 + a_3 \cdot V^3 + a_2 \cdot V^2 + a_1 \cdot V + b_4 \cdot S^4 + b_3 \cdot S^3 + b_2 \cdot S^2 + b_1 \cdot S + \varepsilon \quad (1)$$

where E is the solar radiation intensity, a_i and b_i ($i=1, 2, 3, 4$) are coefficients, and ε is an error term. V and S are the brightness value and the saturation, respectively. These coefficients are determined by the least-squares method.

The following five expressions are introduced and examined:

App.Exp. O:

$$E = a_4 \cdot V^4 + a_3 \cdot V^3 + a_2 \cdot V^2 + a_1 \cdot V + \varepsilon \quad (1-O)$$

App.Exp. I:

$$E = a_1 \cdot V + b_1 \cdot S + \varepsilon \quad (1-I)$$

App.Exp. II:

$$E = a_2 \cdot V^2 + a_1 \cdot V + b_2 \cdot S^2 + b_1 \cdot S + \varepsilon \quad (1-II)$$

App.Exp. III:

$$E = a_3 \cdot V^3 + a_2 \cdot V^2 + a_1 \cdot V + b_3 \cdot S^3 + b_2 \cdot S^2 + b_1 \cdot S + \varepsilon \quad (1-III)$$

App.Exp. IV:

$$E = a_4 \cdot V^4 + a_3 \cdot V^3 + a_2 \cdot V^2 + a_1 \cdot V + b_4 \cdot S^4 + b_3 \cdot S^3 + b_2 \cdot S^2 + b_1 \cdot S + \varepsilon \quad (1-IV)$$

App.Exp. O is expressed by terms up to the fourth-order of V . App.Exp. I is expressed by terms of the first-order of V and S . App.Exp. II and III are expressed by terms up to the second-order and the third-order of V and S , respectively. App.Exp. IV is equal to Eq. (1). App.Exp. O is a reference equation that only uses the brightness value, because the brightness value has the strongest correlation with solar radiation intensity, with regard to color properties.

3.2 Evaluation method

An evaluation of the approximate expressions and the estimation models is executed by the MAE, which is defined as follows:

$$MAE = \frac{1}{n} \sum |E_{es} - E_{ob}| \quad (2)$$

where E_{es} and E_{ob} are the estimated solar radiation intensity and an observed solar radiation intensity, respectively, and n is the number of data points. The accuracy of the estimation model is high when the MAE is small.

3.3 Verification

The approximate expressions shown in Eqs. (1-O) to (1-IV) are derived using data collected on Nov. 1, 2013, which was a typical clear day. The coefficients for these approximate expressions are shown in Table 2. The solar radiation intensity is estimated at 1 min intervals. MAEs for these approximate expressions during the estimation period of Oct. 16, 2013 to Dec. 1, 2013 are shown in Fig. 6. The data collected on Nov. 1 are excluded from the evaluation and as a result, App.Exp. IV gives the most accurate approximation.

Fig. 7 shows the MAE for App.Exp. IV, and the ratio of sunshine duration from Oct. 16 to Nov. 10, 2013. This time period is a part of the estimation period. The ratio of sunshine duration in Fig. 7 represents an average value per hour, from 9:00 to 15:00⁶⁾. The MAE is small when the ratio of sunshine duration is large. These results suggest that a fundamental estimation model should be switched according to weather conditions.

4. Proposal and Verification of the Estimation Method

4.1 Fundamental estimation models

A clear day model and a cloudy day model are developed as fundamental estimation models. These models account for the time zone and weather, because the relationship between solar radiation intensity and color properties present during the morning differs somewhat

Table 2 Coefficients of five approximate expressions

App.Exp.	a_4	a_3	a_2	a_1	b_4	b_3	b_2	b_1	ε
O	-45.598968	54.079992	-18.537219	3.265802				0.016316	0.010542
I				1.674848					0.000161
II			2.191039	0.640254			-0.116816	0.186712	0.008508
III		5.159180	-1.474007	1.213625			-1.166222	0.523020	0.008001
IV	-54.972819	62.409906	-20.448486	3.128226	-2.226192	5.877765	-5.042704	1.404522	0.007367

Fig. 6 MAEs for five approximate expressions from Oct. 16, 2013 to Dec. 1, 2013

Fig. 7 The MAE for App.Exp. IV and the ratio of sunshine duration from Oct. 16, 2013 to Nov. 10, 2013

from that observed in the afternoon and various types of weather are represented during the estimation period. Data collected on Nov. 1, 2013 are shown in Fig. 3(a) and data collected on Oct. 18, 2013, are shown in Fig. 3(b). These data sets are used to represent a typical clear day and a typical cloudy day, respectively, for model development. The coefficients of these fundamental estimation models are shown in Table 3. The clear day and cloudy day models modify the utilized model during the morning and afternoon. Thus, the MAE for the clear day model during the estimation period is 0.0554 kW/m^2 .

Fig. 8 shows MAEs for the clear day and cloudy day models, and the ratio of sunshine duration from Oct. 16 to

Nov. 10, 2013. The MAE of the cloudy day model is large when the sunshine duration is long. MAEs for each type of weather using the clear day and cloudy day models during the estimation period are shown in Fig. 9. The clear day model is superior to the cloudy day model on partly sunny days and clear days. On the other hand, the cloudy day model is superior to the clear day model on slightly cloudy days, cloudy days, and rainy days.

4.2 Hybrid model

The hybrid model is proposed to switch to either the clear day model or the cloudy day model, according to the weather type presented by JMA Okayama Local

Table 3 Coefficients of the clear day and cloudy day models

Model		a_4	a_3	a_2	a_1	b_4	b_3	b_2	b_1	ε
Clear day	AM	-34.435159	41.332928	-13.556825	2.516505	-0.244157	0.570512	-0.517646	0.218396	0.008589
	PM	-71.138893	74.912120	-22.872224	3.122308	-2.250531	6.260219	-5.650032	1.652104	0.006405
Cloudy day	AM	8.431025	3.521971	-1.490907	0.520780	2.960936	-6.153768	3.894548	-0.667177	0.008214
	PM	42.427082	-22.068660	3.866521	0.256767	0.057903	0.092587	-0.339234	0.220859	0.008577

Fig. 8 MAEs for the clear and cloudy day models, and the ratio of sunshine duration from Oct. 16, 2013 to Nov. 10, 2013

Fig. 9 MAEs for each type of weather, using the clear day and cloudy day models, from Oct. 16, 2013 to Dec. 1, 2013

Meteorological Office at 9:00, 15:00 and 21:00⁶⁾. Specifically, the hybrid model uses the clear day model when the weather is clear or partly sunny. Conversely, the model uses the cloudy day model when the weather is slightly cloudy, cloudy, or rainy. The switching schedule of the hybrid model is shown in Fig. 10. The hybrid model changes to one of the AM models at 6:00 and 9:00, while changing to one of the PM models at 12:00 and 15:00.

MAEs for the clear day model, the cloudy day model, and the hybrid model during the estimation period are shown in Fig. 11. The hybrid model improves MAE by 13% as compared to the clear day model. The solar radiation intensity estimated by the hybrid model is shown in Fig. 12, during the period of Nov. 25 to Dec. 2, 2013. This time period is a part of the estimation period. The hybrid

model appears to estimate solar radiation intensity with sufficient accuracy. Fig. 13 shows MAEs for the clear day model and the hybrid model from Oct. 16 to Nov. 10, 2013. The accuracy of the hybrid model is better than that of the clear day model on most days during this time period. In particular, MAEs are improved on cloudy and rainy days (e.g. on Oct. 16, Oct. 18, Oct. 19, Oct. 23, Oct. 26, Nov. 2, Nov. 3, and Nov. 10). However, the MAEs for the hybrid model deteriorate as compared with MAEs for the clear day model on certain days (e.g. on Oct. 17, Nov. 7, and Nov. 9). The reason for this is the difference between the actual weather and the weather used for switching the model. There is a possibility that estimation accuracy improves if the weather type is announced more frequently.

Fig. 10 Switching schedule of the hybrid model

Fig. 11 MAEs for each estimation model from Oct. 16 to Dec. 1, 2013

Fig. 12 Estimated results of the hybrid model from Nov. 25, 2013 to Dec. 1, 2013

Fig. 13 MAEs for the clear day model and the hybrid model from Oct. 16, 2013 to Nov. 10, 2013

5. Conclusion

This paper proposed an estimation method for solar radiation intensity using pictures taken by a web camera. The proposed method switches the estimation models according to the weather type and time zone. The summary of this paper is as follows:

1. A correlation between solar radiation intensity and the color properties of pictures taken by a web camera is investigated. The solar radiation intensity and brightness values show a positive correlation, and the solar radiation intensity and saturation have a weakly negative correlation. On the other hand, there is no correlation between the solar radiation intensity and hue.
2. Five approximate expressions are derived using the observed solar radiation intensity and the color properties of pictures. A fourth-order approximate expression using the brightness value and saturation exhibits the smallest MAE, as compared with other expressions using only low dimensional expressions and the brightness value.
3. A clear day model and a cloudy day model are developed as fundamental estimation models. The hybrid model, which switches to either the clear day model or the cloudy day model according to weather conditions and the time zone, improves the MAE by 13% as compared with the clear day model.

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